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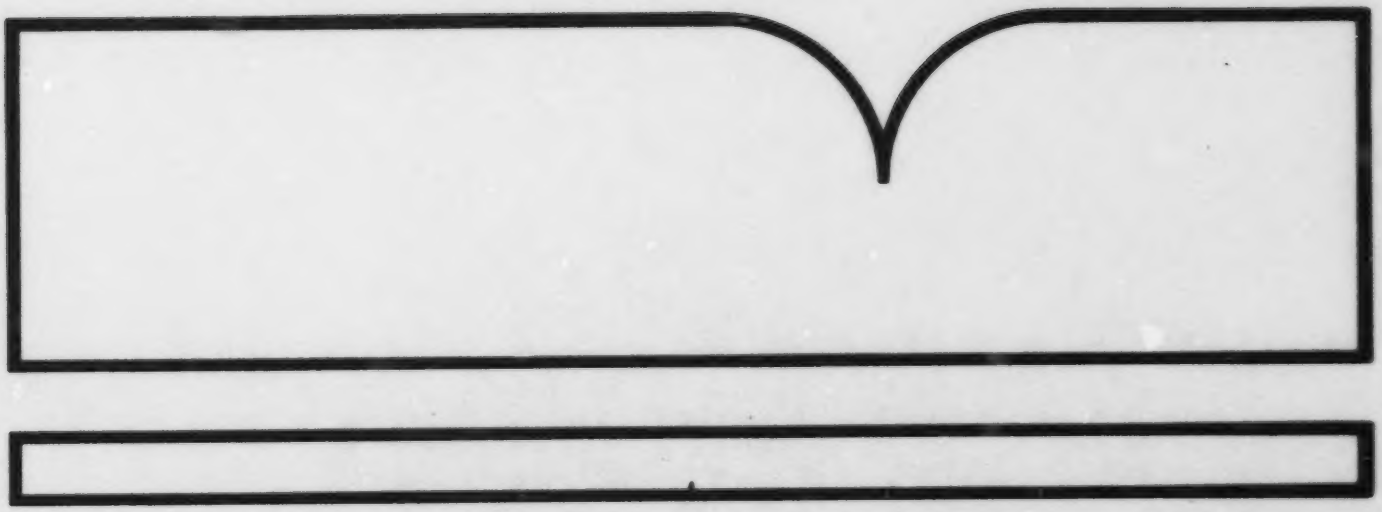

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CHAPTER 28

BIOLOGICAL PROCESSES AFFECTING THE DISTRIBUTION OF POLLUTANTS IN MARINE SEDIMENTS. PART I. ACCUMULATION, TROPHIC TRANSFER, BIODEGRADATION AND MIGRATION

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INTRODUCTION

The seabed is the ultimate sink for virtually every class of marine pollutant. Chlorinated hydrocarbons, petroleum hydrocarbons, metals and radionuclides are deposited in sediments and may persist there long after original sources of contamination are eliminated [1-6]. The sediment reservoir thus becomes a major potential source for recontamination of the sea. The threat posed by this reservoir is dependent on the mechanisms through which pollutants are released from the sediment and made available to the biota. This chapter deals with the biological processes that affect the biogeochemical cycling of contaminants in benthic ecosystems.

Six processes were selected for discussion: bioaccumulation, trophic transfer, migration, biodegradation, biodeposition and bioturbation. The latter two are examined in the second part of our review (Chapter 29, this volume). For review purposes, uptake of pollutants via sediment ingestion is included in the section on bioaccumulation. With the exception of detrital food chains, the discussion of trophic transfer concerns the transport of pollutants from prey to predator. All spatial movements

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in which animals enter or leave areas of sediment contamination are included in the section on migrations. The discussion of biodegradation is restricted to the metabolism of pollutants by benthic animals. The important processes of microbial degradation are beyond our area of expertise and the reader is referred to other reviews [7-11].

BIOACCUMULATION OF POLLUTANTS FROM SEDIMENT

Influence of Sediment Type

Several recent investigations have demonstrated the importance of the presence and kind of sediment in determining the accumulation and effects of pollutants on benthic organisms. Presence of sediment has been shown to decrease accumulation of radiocadmium by the clam *Mya arenaria* [12]; increase elimination of radiozinc by the amphipod *Anonyx* sp [13]; and increase the LC50 of copper for the polychaete *Neanthes arenaceodentata* [14]. The duration of exposure to copper necessary to kill half a test group of *N. arenaceodentata* was longer in mud than in sand [15]. Similarly, less cadmium was accumulated by *M. arenaria* in mud than in sand [12]. Luoma and Jenne [16] found that the surface deposit-feeding clam *Macoma balthica* did not accumulate radiocadmium from organic detritus or organically coated iron oxide particulates, but did accumulate it from uncoated iron oxide particulates and San Francisco Bay sediment. Pollutants bind preferentially to different size classes of sediment and detrital particles [17]. This contributes to differences in the availability of sediment-bound contaminants to species and food chains. The accumulation of radiozinc by the polychaete *Nereis diversicolor* was greater from detrital particles 0.2-2 mm in diameter than from smaller particles, and was greater when zinc was deposited at the sediment-water interface rather than mixed thoroughly within the sediment [18]. Clearly, abiotic factors may control the partitioning and bioavailability of pollutants within benthic ecosystems [16]. Until recently these factors have been largely ignored. Future research should emphasize the relationship between bioaccumulation potential and sediment characteristics, such as mineral composition, oxidation state, shape, size and organic content of particles.

Source Identification: Sediment vs Water

Attempts have often been made to use field data to establish correlations between biological and sediment concentrations of pollutants. For several reasons these efforts have met with variable success. First, only a portion of the sediment-bound contamination is bioavailable, and there is

no simple way of determining the available fraction through the use of extractants [16]. Second, some invertebrates are known to regulate internal pollutant concentrations [19,20] which could lead to spurious correlations between contaminant levels in the sediments and biota. Third, animals accumulate pollutants from water, food and sediment [21,22], and field surveys cannot easily discriminate inputs from multiple sources. Fourth, differences within populations (size, age, microhabitat) in the ability to accumulate pollutants may obfuscate relations between sediment and body burdens. Finally, this correlation assumes an equilibrium between tissue and source concentrations that may rarely, if ever, occur. This is demonstrated in Luoma's [23] study of mercury dynamics in Ala Wai Canal, Hawaii. Accumulation of mercury by the shrimp *Palaemon debilis* occurred rapidly during short periods of storm runoff. Between storms, little of the mercury in the sediment was available to the shrimp. Because depuration was relatively slow, mercury concentrations in the shrimp never reached an equilibrium with either water or sediment sources.

Experimental attempts to determine the relative importance of sediment and water as pollutant sources are usually designed to obtain a concentration factor for each source, i.e., the ratio of the pollutant level in the organism to that of the water or sediment [5,21,22,24]. These factors are invariably much greater for water than sediment, but that does not necessarily mean that water is the more important source. For example, the polychlorinated biphenyl (PCB) concentration factor for *Nereis diversicolor* was much higher in water (800) than in sediment (3.5) [22]; however, when Fowler et al. [22] multiplied these factors by ambient sediment and water PCB concentrations, the dominance of the sediment input became evident. At least 85% of this worm's PCB body burden could be accounted for by uptake from sediment in both coastal and oceanic habitats. Through a similar calculation, Beasley and Fowler [21] found that water was the dominant source of plutonium for *N. diversicolor*. However, sediment still accounted for 17% of the plutonium body burden, despite the fact that its concentration factor was five orders of magnitude less than that of water.

Sediment contaminants can be divided into fractions associated with interstitial water and sediment particles. For several kinds of pollutants the interstitial water fraction has been shown to be most available to the benthos [5,19-21,23]. Roesijadi et al. [5] found that *Macoma inquinata* accumulated similar concentrations of aromatic hydrocarbons regardless of whether they were placed directly in contaminated sediment or held in the water column above the sediment. They concluded that the particulate-bound aromatic fraction was less available than the fraction initially present in interstitial waters and leached to surrounding seawater. The ability of

Nereis succinea and *Palaemon debilis* to accumulate much more radiomercury from terrestrial than from estuarine sediments was correlated with higher ^{203}Hg concentrations in the interstitial waters of the terrestrial sediment [23].

A better understanding of factors controlling the partitioning of pollutants between interstitial water and particulates is needed to explain bioavailability accurately. Bryan and Hummerstone [19,20] showed that zinc and copper were more concentrated and available to *Nereis diversicolor* in the oxidized, surface sediment layer than in reduced subsurface layers. Beasley and Fowler [21] applied a sediment-water distribution coefficient to the interstitial water-particulate interface and calculated that enough plutonium is present in interstitial water to account for the relatively small sediment contribution of plutonium to *N. diversicolor*. Conversely, sediments were the dominant source of PCB for *N. diversicolor*, but PCB concentrations in interstitial water were far too low to provide more than a fraction of the sediment input [22]. Thus, for pollutants such as PCB, the particle-bound fraction had greater bioavailability [22,25].

The relative importance of sediment as a pollution source increases as water column concentrations decrease, due to pollution abatement and dilution. Pesticide residues in filter-feeding molluscs suggest a major decline in the chlorinated hydrocarbon content of estuarine waters of the United States during the past decade [26]. Much of this material has accumulated in the sediment reservoir. Before source control was initiated, approximately 200 metric tons of DDT were deposited in the sediments in a 50-km^2 area around the sewage outfalls of the Palos Verdes Peninsula, California [4,27]. By 1975 the input of DDT via the outfalls had decreased by an order of magnitude, but the median total DDT concentration in the sediment had dropped by a factor of only 1.6 (19 to 12 ppm). Young and his colleagues [4,27] believed that the contaminated sediments might continue to cause excessive DDT levels in benthic fishes for many years.

Mechanisms of Accumulation and Adaptation

Pollutants can be accumulated through adsorption to the body wall or exoskeleton; absorption through the integument, gills or other respiratory surfaces; or ingestion of sediment, food and water followed by absorption through the gut. Once inside the body pollutants are deposited within various tissues or eliminated by egestion, excretion, molting or production of mucus [3,6,13,19,20,22,28-30]. The relative contributions of these processes in determining the accumulation and flux of pollutants through benthic invertebrates are poorly understood.

In heavily contaminated sediments, lethal internal concentrations may

be reached by species that are unable to adapt to the presence of pollutants in water or sediment. Thomas [31,32] found that *Mya arenaria* mortality in Chedabucto Bay, Nova Scotia following a Bunker C oil spill was directly proportional to the amount of oil in the sediment. Juvenile *M. arenaria* were able to set and grow normally in areas where the uppermost sediment layer had been cleansed of oil by weathering or other processes, but when they reached a size that permitted burrowing into contaminated subsurface layers, growth was reduced and death resulted [33,34]. The maximum body burden of petroleum hydrocarbons that fiddler crabs (*Uca pugnax*) could tolerate in oiled marshes was about 280 ppm [6,35]. In certain instances the rate of accumulation determines toxicity. McLusky and Phillips [36] found that the uptake rate of copper by the polychaete *Phyllodoce maculata* was proportional to the external concentration. Worms survived for three weeks and reached a Cu body burden of 568 ppm when exposed to a 0.06-ppm copper solution, but they died within a week at a body burden of only 270 ppm when exposed to a 0.1-ppm solution. The critical uptake rate of copper for *P. maculata* was 25 ppm/day.

A classic example of the adaptation of a benthic invertebrate to sediment pollution is provided in Bryan and Hummerstone's [19,20] study of the response of *Nereis diversicolor* to metal contamination of estuaries in the mining region of Southwest England. Through field observations in estuaries exposed to different kinds and degrees of metal pollution, they found that the concentration of copper in *N. diversicolor* was roughly related to sediment concentration, but the zinc body burden was relatively constant and appeared to be regulated. Much of the zinc and copper in interstitial waters is available to the worms in an inorganic form or weakly bound by soluble organic compounds. Adaptations of *N. diversicolor* to zinc and copper are different, appear to be genetically determined, and have probably evolved separately. Zinc is regulated through a reduction in the permeability of the body surface and a greater ability to excrete the metal. Conversely, copper is absorbed more rapidly in resistant worms, but once in the body it is detoxified by a chelation system and stored in the nephridia and epidermis. Similarly, the lead tolerance of the isopod *Asellus meridianus* may be genetically determined, and different physiological mechanisms may account for this species' tolerance to lead and copper [37]. The degree of toxicant tolerance generally increases with levels of environmental contamination and is often based on pollutant-specific mechanisms. Thus, Luoma [38] suggested that a comparative study of the relative susceptibility of different species and populations to different pollutants could be used to determine: (1) whether trace contaminants are affecting organisms in a given situation, and (2) which contaminants are exerting the more significant effect.

Several recent contributions have greatly extended our knowledge of the processes through which metals are sequestered within invertebrate tissues. George et al. [39] have shown that oysters (*Ostrea edulis*) detoxify copper and zinc by compartmentation within membrane-limited vesicles of different amoebocytes. The copper and zinc were removed by active uptake from the serum and reached concentrations as high as 13,000 ppm Cu and 25,000 ppm Zn in the amoebocytes. Similarly, barnacles (*Balanoides balanoides*) accumulated zinc and copper in different kinds of granules within parenchyma cells [40]. Talbot and Magee [41] have isolated a low-molecular-weight metal-binding protein from mussels (*Mytilus edulis*) in cadmium-polluted areas of Corio Bay, Australia. They believed that the synthesis of this protein was induced as a regulatory mechanism to avoid the toxic effects of cadmium, copper and zinc.

Selection in polluted habitats can result in resistant populations that superficially resemble normal communities. Bryan [3,28,29] noted that the metal tolerance of *Nereis diversicolor* may extend to a variety of other species in metal-contaminated estuaries. Adult polychaetes (*Neanthes arenaceodentata*) developed a resistance to petroleum hydrocarbons that Rossi and Anderson [42] attributed to genetic selection. Short-term selection after the West Falmouth oil spill resulted in the dominance of a specific genotype of the opportunistic polychaete *Capitella capitata* [43]. Spies and Davies' [44] survey of the infauna in areas of natural oil seeps where sediments contain over 3000 ppm hydrocarbons revealed a benthic assemblage that is remarkably similar in community structure and dominant species to the benthos of a control area. These examples indicate the need for additional research on genotypic and phenotypic adaptations to environmental contamination.

Bioaccumulation as a Transport Mechanism

Benthic organisms are able to remove pollutants from both particulate and interstitial components of the sediment reservoir. However, when compared to abiotic processes, bioaccumulation would first seem to be a minor transport process. Sediment concentration factors are less than unity for many contaminants. Thus, the biota generally contains only a small fraction of the pollutants in benthic ecosystems. For example, Renfro [1] estimated that a population of *Nereis diversicolor* at a density of 50 worms/m^2 would accumulate only 0.08% of the zinc content of the upper 2 cm of the sediment layer. Nonetheless, this biological portion is qualitatively different from other segments of the sediment reservoir. By definition it is the component that has entered living tissue and thus assumes a significance far beyond its size.

TROPHIC TRANSFER

Predator-Prey Interactions

Teal's [45] observation that there are more gaps than knowledge about the food web transfer of petroleum hydrocarbons applies equally well to all classes of marine pollutants. One major gap concerns the transfer of contaminants from the tissues of infaunal and epibenthic organisms to the demersal and pelagic species that feed on them. This trophic link is of obvious importance to the mobilization of the sediment pollutant reservoir.

Laboratory experiments indicate that certain metals can be transferred very effectively from benthic invertebrates to their predators. Much of this research has involved the polychaete *Nereis diversicolor* as the prey species. Elder et al. [46] demonstrated that *N. diversicolor* readily accumulates PCBs from sediments, and they believed that the worms could act as a PCB source for predators. When Bryan [3] fed metal-contaminated *N. diversicolor* to *Carcinus maenas*, this crab absorbed 31% of the copper, 58% of the zinc and 35% of the iron in its prey. Bryan [29] noted that in most cases reported in the literature, food and particulates were more important metal sources than water, but he cautioned that such generalizations may be dangerous.

In a series of publications, R. J. Pentreath has examined the transfer of radionuclides from labeled *Nereis diversicolor* to plaice (*Pleuronectes platessa*) and thornback rays (*Raja clavata*) [47-53]. The basic experimental design was to contaminate the polychaete by exposure or direct injection, feed one or more individuals to the fish and, after 4-8 days, determine the accumulation and percent retention in the whole body and individual organs of the fish. Pentreath found that food was a much more important source than seawater for the accumulation of nuclides of zinc, manganese, iron and cobalt. These metals were transferred from labeled *N. diversicolor* to the internal organs of the plaice with whole body retention of 3.5% for ^{58}Co, 18.2-35.7% for ^{65}Zn, 32.0% for ^{59}Fe and 36.9-40.3% for ^{54}Mn. Both thornback rays and plaice retained a much larger proportion ($\sim$ 90%) of organic mercury than inorganic mercury ($<$ 15%) from the labeled polychaetes. Pentreath [52,53] has recently shown that retention of plutonium is low ($<$ 5%) relative to the metals studied earlier. There was an interspecific difference in accumulation of plutonium. Plaice did not accumulate ^{237}Pu in any internal organ other than the digestive tract. However, small amounts of ^{237}Pu were detected in the liver and other organs of the thornback ray. While feeding on infaunal organisms, demersal fishes and other predators may ingest sediment. Pentreath [52] simulated this "trophic" link by feeding ^{237}Pu-labeled

sediment pellets to plaice, but there was no accumulation beyond the digestive tract. The same result was obtained when ^{237}Pu-labeled crab (*Carcinus maenas*) hepatopancreas was fed to plaice.

Cross et al. [13] examined the trophic transfer of radionuclides from brine shrimp to the amphipod *Anonyx* sp. After feeding on a labeled brine shrimp, the amphipods retained an average of 56% of the ^{65}Zn, $<10\%$ of ^{46}Sc and ^{144}Ce and no detectable ^{51}Cr. Experiments were also conducted in which *Anonyx* accumulated radionuclides from seawater. The source of ^{65}Zn greatly influenced loss at ecdysis. When amphipods molted, those exposed to labeled seawater lost 20% of their radioactivity, while those that fed on labeled brine shrimp lost only 2%. The difference was attributed to greater exoskeleton absorption during accumulation from seawater.

Renfro et al. [30] compared the long-term accumulation of ^{65}Zn from food and water by a fish (*Gobius* sp.), crab (*Carcinus maenas*) and shrimp (*Lysmata seticaudata*). Two experimental groups of each species were placed in the same tank containing ^{65}Zn-labeled seawater. One group was fed labeled food and the other nonradioactive food. After three months the ^{65}Zn activities were higher in the food plus water exposure groups for all three species, but the results were statistically significant only for the goby. Renfro et al. concluded that food is not as important a source of zinc as suggested by earlier research. They based their statistical analysis on whole body radioactivity that did not discriminate between external and internal concentrations. However, they did measure the loss of ^{65}Zn activity after molting and found that the crabs lost an average of 61% and the shrimp an average of 45%. If most of the ^{65}Zn contamination of crustacean exoskeletons is associated with water exposure, as suggested by Cross et al. [13], significant concentration differences may occur in internal organs such as the hepatopancreas, but not be indicated by whole body burdens. The internal burden may have greater potential for transfer to predators because of its incorporation into the body's protein pool.

These experiments leave little doubt that food can be a significant source of contamination. There appear to be major interspecific and chemical differences in trophic transfer of pollutants. A critical question that has not been addressed adequately is the frequency of exposure and level of accumulation at which deleterious effects will become evident. Experiments designed to examine this question should simulate real examples of contaminated environments. For example, designs similar to those of Pentreath [47-53] in which a limited quantity of food is made available to predators would be appropriate to determine the threat that a spatially restricted area of contamination, such as a dump site, might pose to a transient fish population feeding on benthic invertebrates within

the site. Long-term trophic exposure such as that employed by Renfro et al. [30] would be more useful in assessing the effects of persistent or widespread contaminants that would impose chronic stresses on resident populations. However, the success of long-term experiments is often dependent on the extent to which a species' life history requirements can be simulated in the laboratory.

Effects of contaminants on food web interactions can alter the trophic transport of pollutants. Slight deterioration of escape or predator avoidance behavior can have lethal consequences. Increased vulnerability to predators has been suggested for the clams *Mya arenaria* and *Macoma balthica* which left its burrows after an oil spill [31,32,54], and for the fiddler crabs exposed to oil and DDT in contaminated marshes [17,35]. Tagatz [55] experimentally demonstrated an increased level of predation by pinfish (*Lagodon rhomboides*) on grass shrimp (*Palaemonetes vulgaris*) after exposure to sublethal concentrations of the insecticide mirex. A reduction in energy flow through an experimental microcosm exposed to three concentrations of copper for 100 days was reported by Saward et al. [56]. The microcosm included a phytoplankton assemblage, filter-feeding clams (*Tellina tenuis*) and juvenile plaice (*Pleuronectes platessa*), which naturally feed on tips of the clam siphons. Accumulation of copper in clam flesh and plaice viscera was dose dependent. All copper concentrations (10, 30 and 100 μg/l) inhibited algal productivity. Saward et al. [56] believed that the reduction in food available to *T. tenuis* accounted, at least in part, for the reduced growth of the clams and that this, in turn, reduced the growth of the plaice.

It is very difficult to discriminate between food, seawater and sediments as pollutant sources on the basis of field surveys of contaminant concentrations in the biota. However, a number of investigators have interpreted body burdens in terms of trophic relations. Carey [57], for example, traced the fate of ^{65}Zn within an echinoderm food chain on the continental shelf off Oregon. The ^{65}Zn was released from the Hanford reactors on the Columbia River and was not detectable in the sediments at the sampling stations on the shelf. Carey believed that deposit-feeding brittle stars (*Ophiura* spp.) concentrated ^{65}Zn through sediment ingestion. The brittle stars were the prey and chief source of radionuclides for the starfish *Luidia foliolata*.

Several investigators have interpreted the ability of benthic invertebrates to accumulate pollutants in terms of their feeding type or trophic position. Phelps et al. [58] examined the distribution of stable elements among polychaetes off the West Coast of Puerto Rico. They found that nonselective deposit-feeders had consistently higher zinc concentrations, while the concentration of iron, samarium and scandium were highest in filter-feeders and selective deposit-feeders. These relationships reflected the distribution

of the elements: zinc was more available in the interstitial water of subsurface sediments, while iron, samarium and scandium were found in particulate matter at the sediment-water interface. Phelps and Myers [59] obtained somewhat different results in their study of the distribution of three metals within invertebrates of Narragansett Bay, Rhode Island. "Sediment-water interface feeders" such as *Rithropanopeus* and *Nassarius* had the highest levels of zinc and silver. Filter-feeders, e.g. *Mercenaria* and *Mya*, were highest in chromium. "Subsurface feeders" (*Glycera* and *Nephtys*) had the lowest accumulation of the three metals. Phylogenetic differences between feeding groups may confound such comparisons. Roesijadi et al. [5] reported that the accumulation of petroleum hydrocarbons was generally greater in deposit-feeders (*Macoma inquinata* and *Phascolosoma agassizii*) than in the suspension-feeder *Protothaca staminea*, but they cautioned that characteristics other than feeding type may influence accumulation patterns.

Biomagnification

Biomagnification of pollutants can be examined by comparing concentrations at successive trophic levels. Food chain magnification is an intuitively appealing concept for many ecologists. However, Isaacs [60] and others have recently argued that pelagic marine food webs are typically unstructured, with diffuse energy flow patterns including movement from higher to lower trophic levels. The lack of structure and unidirectional flow that are characteristic of classical food chain models may prevent the amplification of pollutants at higher levels.

Burns and Teal [6] found no evidence for food chain magnification of petroleum hydrocarbons among marsh animals exposed to the West Falmouth spill. The only animal they tested that contained more oil than its food was the herring gull (*Larus argentatus*). The fiddler crabs (*Uca pugnax*) in the marsh quickly achieved a body burden of oil that did not decrease for four years after the spill. Burns and Teal believed that this was the maximum internal concentration that the crabs could survive. In a review article on food chain transfer of hydrocarbons, Teal [45] noted a general lack of belief in the magnification concept. Varanasi and Malins [61] doubted that food was a major route for the accumulation of petroleum hydrocarbons in higher trophic levels because of the ability of most marine organisms to extract substantial amounts of oil from seawater.

There is evidence for food web magnification of certain pollutants other than oil. Goerke et al. [62] examined the distribution of organochlorine compounds among animals in the Weser estuary of West Germany. PCB concentrations were higher in a predatory flatfish (*Solea solea*) than

in deposit- and filter-feeding benthic invertebrates (*Crangon crangon, Arenicola marina, Mya arenaria* and *Cerastoderma edule*). Goerke et al. [62] interpreted this result as pollutant magnification within lower trophic levels. They noted, however, that these species are not linked in a common food chain. Phylogenetic and habitat differences between these species could also influence PCB partitioning.

Young and Mearns [63] have recently reported preliminary results of their research on pollutant flow through three marine food webs in the Salton Sea, Newport Bay, California, and off Palos Verdes Peninsula near the Los Angeles County sewage outfall. They attempted to assign species to one of five trophic levels (primary producer, herbivore, primary, secondary or tertiary carnivore), but most species were assigned intermediate positions. Young and Mearns then examined the distribution of metals and chlorinated hydrocarbons in relation to trophic position. No relationship was evident for most trace metals (Ag, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn). Most metal concentrations were considerably lower in predatory fishes than in benthic invertebrates from the contaminated Palos Verdes shelf. However, in all three food webs there were distinct increases in mercury, total DDT and PCB 1254 with increasing trophic level. For each of these pollutants the increase in concentration from the lowest to the highest trophic level ranged from a factor of about 3 to over 20.

The literature certainly indicates that there are major differences between pollutants in their potential for biomagnification. The relatively unstructured nature of certain marine food webs may limit, but does not necessarily preclude, magnification. Young and Mearns' [63] report shows that pollutants of major concern to man are among those whose concentrations can increase with trophic level. Future research must examine the chemical and biological mechanisms that control the magnification process.

Detrital Food Chains

An important aspect of the trophic transport of pollutants within benthic ecosystems that should be emphasized in future research is the contamination of detrital food chains. A variety of marine macroalgae and spermatophytes are known to accumulate trace metals and chlorinated hydrocarbons from seawater and sediment, often with very high concentration factors [2,55,64-70]. Bryan [64] found that once ^{65}Zn is absorbed from seawater by the brown alga *Laminaria digitata* it becomes tightly bound to the plant, possibly in polysaccharide or protein pools. Similarly, Seeliger and Edwards [67] reported that the majority of dissolved inorganic copper taken up by the red algae *Ceramium pedicellatum* and *Neogardhiella*

baileyi will eventually become available to consumers, either as particulate detritus or dissolved organic matter. Only a small portion (< 10%) of the copper is recycled in dissolved inorganic form.

In their exemplary study of metal distribution in an eelgrass (*Zostera marina*) community, Wolfe et al. [2] estimated that 55% of net eelgrass productivity is consumed as detritus by the macrofaunal benthos. Odum et al. [17] demonstrated deleterious effects to fiddler crabs (*Uca pugnax*) following consumption of DDT-contaminated detritus.

Thus, the literature provides strong evidence that plants accumulate high concentrations of pollutants, and that benthic invertebrates are the principal consumers of contaminated plant detritus. Laboratory microcosms that simulate detrital food chains could provide a useful research tool for comparative study of pollutant dynamics within benthic ecosystems.

MIGRATIONS

The term migration is used here in the sense of spatial movement of animals entering or leaving areas of sediment contamination on seasonal, daily or other temporal intervals. Seasonal migrations in estuarine and coastal waters have been described for a tremendous variety of demersal fishes and epibenthic invertebrates. Many fishery species make such migrations, e.g. crabs, shrimp, lobsters and flatfish. There have been several recent reports on the nocturnal movements of infaunal invertebrates, especially polychaetes and amphipods [71,72]. Dean [71,73] found that adults of many species rise into the water column and are transported to new locations. This diurnal activity is not necessarily related to reproduction. Davis [72] believes that dispersal from "crowded or deteriorating habitats" is the most likely explanation of the nocturnal movements of benthic invertebrates.

The contribution of migration to the flux of pollutants within ecosystems has rarely been examined. Wolfe et al. [2] found that the total amounts of Mn, Fe, Cu and Zn involved in the seasonal migrations of fishes and invertebrates represents only a "minute fraction" of the annual sediment accumulation of these metals within eelgrass (*Zostera*) beds. The body burden of diurnally and seasonally migrating animals may constitute a much larger proportion of the pollutant pool available to higher trophic levels through predation. Schoor and Newman [74], for example, believe that swimming juvenile lugworms (*Arenicola cristata*) can transmit the insecticide mirex to predators.

Migrating animals may be the first colonizers of disturbed habitats. Thus, bioturbation by larger animals can begin prior to successful larval recruitment. Burns and Teal [6] found that the recolonization of the oiled

West Falmouth, Massachusetts marsh by fiddler crabs (*Uca pugnax*) was dependent initially on the immigration of adults from unoiled areas. Burrows built by the early colonizers aided the dissipation of oil from subsurface sediments.

The release of gametes or brooded young from contaminated adults could provide a mechanism for the transport of pollutants in benthic ecosystems. However, Klöckner [75] recently demonstrated that cadmium concentration in egg masses of the polychaete *Ophryotrocha diadema* were low (12–280 ppm) compared to parental organisms (up to 1700 ppm) that had been exposed to 1 ppm Cd in seawater for 64 days. Cadmium content of egg masses did not increase over three generations. The mechanism through which *Ophryotrocha* eggs avoid contamination during oogenesis is not known.

BIODEGRADATION OF POLLUTANTS BY BENTHIC ANIMALS

Research on the ability of benthic animals to metabolize pollutants has been limited almost entirely to the degradation of petroleum hydrocarbons. The metabolism of aromatic hydrocarbons is catalyzed by aryl hydrocarbon hydroxylase enzymes found in the endoplasmic reticulum of animal cells [61,76]. This enzyme system metabolizes toxic, lipid-soluble hydrocarbons to water-soluble, polar compounds that can be excreted [44,77].

Aryl hydroxylase activity has been demonstrated in a number of demersal fishes, epibenthic crustaceans and echinoderms, and infaunal polychaetes [61,76-80]. The adaptive significance of this enzymatic system is indicated by the experiments of McCain et al. [81], who exposed English sole (*Parophrys vetulus*) to sediments contaminated with Alaskan North Slope crude oil. During the first 11 days of exposure, the fishes readily accumulated alkane and aromatic petroleum hydrocarbons in their skin, muscle and liver. McCain et al. [81] believed that the induction of the aryl hydrocarbon hydroxylase system may have been responsible for the nearly complete depuration of aromatics by day 60 of continuous exposure to oiled sediment.

Even though an animal may have the ability to metabolize foreign hydrocarbons, it may not be able to effectively remove pollutants from its tissues by metabolism alone. Burns [77] demonstrated that fiddler crabs (*Uca pugnax*) have the enzymatic systems necessary to metabolize aldrin and naphthalene. However, the body burdens of petroleum hydrocarbons of crabs collected over a three-year period in an oiled marsh (West Falmouth, Massachusetts) were consistently much greater than those of crabs from a clean marsh. Burns [77] calculated that it would take three years for a

crab from the oiled marsh to metabolically remove the oil from its tissues. She concluded that *U. pugnax* is not able to increase significantly the rate of petroleum hydrocarbon metabolism, either by enzyme induction or genetic selection.

Aryl hydroxylase activity is not present in several species of bivalve and gastropod molluscs [61,76,82]. Vandermeulen and Penrose [82] found that soft-shell clams (*Mya arenaria*) and blue mussels (*Mytilus edulis*) that had been exposed to oil pollution for short (4 days) and long (6 years) periods were unable to metabolize benzopyrene. The depuration pattern of *M. areanaria* consisted of a rapid initial loss of oil coating the mantles, gills and gut, followed by a very slow decline in tissue-bound hydrocarbons. Up to 40% of the initial petroleum hydrocarbon body burden was still present after 75 days of depuration in oil-free aquaria. Vandermeulen and Penrose concluded that the tendency of these molluscs to accumulate aromatic hydrocarbons and their inability to metabolize or depurate oil provides an opportunity for the introduction of unaltered petroleum hydrocarbons into marine food webs.

Degradation of pollutants by macrofauna seems much less important than microbial degradation in determining the fate of pollutants [83]. However, the possession of effective detoxification systems is obviously of adaptive significance to individual organisms exposed to contaminated sediments. The presence and effectiveness of aryl hydrocarbon hydroxylase and other detoxifying enzyme systems should be examined in a broader taxonomic range of benthic invertebrates. From an ecological perspective it is important to learn if there is any relationship between the presence of these systems and the greater stress tolerance of opportunistic species that are the early colonizers of contaminated sediments.

SUMMARY

Much remains to be learned about the biological processes that affect pollutant dynamics in marine sediments. Historically, marine pollution research has emphasized "water quality" with relatively little attention having been given to the seabed, either as a source or site of contamination.

There is a great need for additional research on factors controlling the bioavailability of sediment-bound contaminants. Relations between bioaccumulation potential, sediment type and the partitioning of pollutants between interstitial water and particulates have seldom been examined. Physiological mechanisms of accumulation and adaptation have been described for only a few species and pollutants. The importance of natural selection in the response of benthic populations to sediment contamination deserves much more study.

Pollutants differ markedly in their potential for accumulation, trophic transfer and magnification within marine food webs. Detrital food chains seem particularly vulnerable to contamination and could be simulated in microcosms for comparative study of pollutant dynamics within benthic ecosystems.

Migrations appear to be a minor transport mechanism, but may be very significant in the recolonization of disturbed habitats.

Effective detoxification of petroleum hydrocarbons through enzymatic reactions has been described for several fishes and a few invertebrates. This ability should be examined in relation to opportunistic life history strategies.

The literature we have reviewed is restricted to a rather narrow phylogenetic and ecological perspective. Although population studies are not uncommon, rarely have multispecies interactions been examined. Experimental research has concentrated on only a few species. If the polychaete *Nereis diversicolor* is excluded, there are few data on the infauna relative to the epifauna. There is almost no information about meiofaunal species (nematodes, oligochaetes, etc.) or major taxa like amphipods and echinoderms. By contrast, natural benthic assemblages contain a tremendous richness of species with a diversity of feeding mechanisms, behavior repertoires, sizes and shapes. They may possess a variety of unknown or poorly understood mechanisms that affect pollutant transport within sediments.

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